Multisensory Effects of Force Field Adaptation

by

Brandon M. Sexton

Submitted to the faculty of the University Graduate School
in partial fulfillment of the requirements
for the degree
Master of Science
in the Department of Kinesiology of
Indiana University
July 2017

Accepted by the Graduate Faculty, Indiana University, in partial fulfillment of the requirements for the degree Master of Science.

Hannah J. Block, Ph.D.

Thesis Committee

David M. Koceja, Ph.D.

Aina Puce, Ph.D.

July 3, 2017

Abstract

Sensory and motor systems in the brain are highly interconnected and interact in complex ways, making it difficult for clinicians to determine which system is impaired and which to target with interventions after a stroke, for example. In addition, sensory and motor processes are inseparable during natural behavior. Sensory information contributes to motor responses, making it difficult to study sensory and motor processes independently. For example, to plan an accurate reach, the brain must have an accurate initial estimate of the hand's position. This information can be encoded by both vision, via the image of the hand on the retina, and proprioception (position sense), via sensors in the joints and muscles. The brain is thought to weight and combine available sensory estimates to form an integrated multisensory estimate of hand position with which to guide movement. Motor learning studies have suggested that when learning to move straight ahead despite a force field pushing the hand to the right or left, changes are not only made to the motor system, but also to the proprioceptive estimate of hand position. However, it is unknown whether force field adaptation affects multisensory perception. Given that multisensory integration plays a key role in movement planning, one possibility is that force field adaptation affects all relevant sensory modalities similarly. Alternatively, the sensory effects of force adaptation may be specific to proprioception. I worked on developing an experimental paradigm to address this question in healthy adults. Subjects completed two experimental sessions, a force field session and a null field session. Before and after the adaptation block of reaches with the right hand, subjects completed a sensory estimation task in which they pointed with the left hand to the perceived position of the right hand using vision, proprioception, or both. Group results suggest that both visual and proprioceptive estimates of right hand position were systematically realigned after force field learning, supporting the idea that motor learning has multisensory effects.

Table of Contents

List of Tables and Figures

Introduction

Motor and sensory systems are highly interconnected in the brain. Such connections have been characterized in rats, involving visual cortex (Miller & Vogt, 1984) and between posterior parietal cortex, the frontal eye fields, and rostral and dorsal premotor cortex (Leichnetz, 2001). Areas thought to be pure motor regions, such as primary motor cortex, have been found to have sensory receptive fields (Mattar, Darainy, & Ostry, 2013). Somatosensory receptive fields have been found in primary motor and premotor cortices, as well as visual and auditory receptive fields in premotor cortex (Ostry & Gribble, 2016).

In addition, sensory and motor processes are inseparable during natural behavior. Sensory information contributes to motor responses, making it difficult to study sensory and motor processes independently. However, it is important to investigate the separate contributions of these processes to behavior. For example, physical therapists and other clinicians may need to determine which system changes due to an intervention. This could provide information about what therapy protocols may best suit individuals with sensory or motor deficits.

To make accurate movements, the brain is thought to have mechanisms that correct errors in both sensory and motor systems. A major challenge is the determination of whether errors are in the body, world or both (Henriques & Cressman, 2012). An internal model is a way the brain assigns credit for error to different systems (e.g. sensory or motor) to improve performance (Henriques & Cressman, 2012). The brain is thought to make predictions about the sensory consequences of a movement with forward models. These predictions are compared to the sensory feedback after the motor command is executed. If there is a mismatch between predicted and actual sensory feedback, the forward model is updated to make more accurate predictions.

Sensory systems also play a role in accurate movement. For example, to plan an accurate reach, the brain must have an accurate initial estimate of the hand's position. This information can be encoded by both vision, via the image of the hand on the retina, and proprioception (position sense), via sensors in the joints and muscles. The brain is thought to weight and combine available sensory estimates to form an integrated multisensory estimate of hand position with which to guide movement (Ghahramani, Wolpert, & Jordan, 1997). Multisensory integration can respond to changes in the body or environment that affect sensory perception. For example, down-weighting vision with a decrease in illumination results in a multisensory estimate that relies more on proprioception. This is relevant for clinical populations with sensory deficits, such as stroke (Carey & Matyas, 2011). With many sensory systems working together to reduce the error, utilizing proprioceptive feedback may help reduce conflicting sensory information (Henriques & Cressman, 2012).

Motor learning studies have suggested changes are not only made to the motor system, but also to the sensory systems in the brain (Ostry & Gribble, 2016), perhaps because of the many connections between the regions. These motor learning studies have subjects perform reaching movements with a perturbation such as a force field, with a robotic manipulandum applying programmed forces to the hand, which grasps the manipulandum handle during reaches (Mattar et al., 2013). During a rightward force field, when the subject reaches to a straight-ahead target with the manipulandum, the robot applies a force pushing the subject to the right. Initially the subject makes rightward errors, but error magnitude is gradually reduced through trial-and-error practice. Motor learning utilizing a force field has been documented in the literature with error gradually reducing until performance is similar to baseline. When the perturbation is suddenly removed, there is a negative after effect in the direction opposite of the force field,

demonstrating that the brain has used the movement error information to update its internal models (Mattar et al., 2013; Ostry & Gribble, 2016). Adaptation to a force field perturbation is thought to be associated with changes in sensory systems (Mattar et al., 2013). Recent studies have found somatosensory shifts in the subject's perceptual boundary (Mattar et al., 2013; Ostry & Gribble, 2016) while other studies have suggested visual (Brown, Wilson, Goodale, & Gribble, 2007) and auditory changes (Nasir & Ostry, 2009). The perceptual boundary is the point where subjects are equally likely to think their hand is left or right of a given point. For example, if a subject reaches to targets with a rightward force field, following the force field, their perceptual boundary should shift in the opposite direction of the force (Mattar et al., 2013).

An important question is whether force field adaptation affects multisensory perception. Given that multisensory integration plays a key role in movement planning, one possibility is that force field adaptation affects all relevant sensory modalities similarly. In that case, we would expect to see a spatial shift, or realignment, in visual perception of hand position similar to that previously observed in proprioception. Alternatively, the sensory effects of force adaptation may be specific to proprioception. In that case, we would predict realignment in proprioception, but not in vision. This would mean that vision and proprioception are left misaligned with each other. Either outcome would give us new information about how multisensory processing interacts with motor learning.

Methods

Healthy right-handed subjects with no history of neurological impairments performed two sessions each, scheduled at least 4 days apart. Subjects were randomly placed into either the leftward or rightward force field group. Each session involved blocks of trials with two different tasks: a sensory estimation task to assess visual and proprioceptive alignment, which was

performed using a touchscreen apparatus, and a reaching task in which subjects grasped the handle of a robotic manipulandum to make movements. All blocks were the same across the two sessions except the adaptation block of the reaching task. During the null force session, subjects did not experience a force perturbation on any of the reaching trials. In the real force session, subjects encountered a leftward (counter-clockwise) or rightward (clockwise) force perturbation during the adaptation block.

Because this was a new experimental paradigm in our lab, I piloted nine versions of the task (Table 1) before arriving at a version that consistently replicated the proprioceptive realignment observed in the literature. The methods and results below pertain to version nine, which was completed successfully by 36 subjects (age 23.3 ± 4.3 years, 16 female). Each session consisted of 7 blocks of trials: baseline reaching with the left and right hands; pre-adaptation sensory alignment task; adaptation block of reaching with the right hand; post-adaptation sensory alignment task; and washout reaching with the left and right hands (Figure 1A). Subjects were seated in front of a reflected rear projection apparatus, such that the task display appeared to be in the same horizontal plane as the KINARM robotic manipulandum (BKIN Technologies).

Table 1. Overview of task versions during development of the experimental paradigm. In total, 153 subjects were tested across all nine task versions.

Version	Protocol
1	Robotic reaching task consisted of four start positions and four target positions. Movement time was 275-350 ms. Subject used right index finger as target in sensory task. Subject walked from the VR apparatus to the robot between blocks.
2	We thought the target hand in the sensory task should be in a posture more similar to the reaching task, so subjects used right thumb as target in sensory task. Subject walked from the VR apparatus to the robot between blocks.
3	To be more similar to the literature, reaching task had one start position and one target position. Movement time was 575-650 ms and the number of adaptation trials was increased to 96. All of these changes were made to make our task more comparable to Ostry et al., 2010. Subject walked from the VR apparatus to the robot between blocks.
4	The fixation cross was removed from the sensory task because subjects were often pointing to it rather than the target. Subject walked from the VR apparatus to the robot between blocks.
5	The fixation cross was placed back into the sensory task, but as the word "EYES" in red rather than a cross, to remind subjects that their eyes are supposed to go there, not their hand. We also made the force perturbation into a curl field: rightward equals clockwise, leftward equals counterclockwise. This was to be more like Ostry, and may be more natural. Subject walked from the VR apparatus to the robot between blocks.
6	Subjects were blindfolded when they walk from the VR apparatus to the robot because we thought the sensory information obtained while walking back and forth might diminish any effect of the reaching task on sensory alignment.
7	Subjects grasped a replica handle just like the robots' as the proprioceptive target on the sensory task, to make hand/arm posture and tactile feedback more consistent across the two tasks. Subjects were still blindfolded when they walked from the VR apparatus to the robot.
8	Subjects used the replica handle to find the rough and smooth tactile markers on the sensory task.
9	Subjects completed all trials, sensory and reaching, in the same position. Subjects were restrained at the waist, shoulder, and head when completing the sensory and reaching tasks. A smaller touchscreen, for the sensory task, was placed at the same level as the robotic manipulandum. The touchscreen could be slid into place for the sensory blocks without moving the subject. These changes were made after a consultation with Dr. Ostry, who told us the sensory effects of the reaching task might be reduced if the subject is able to move around.

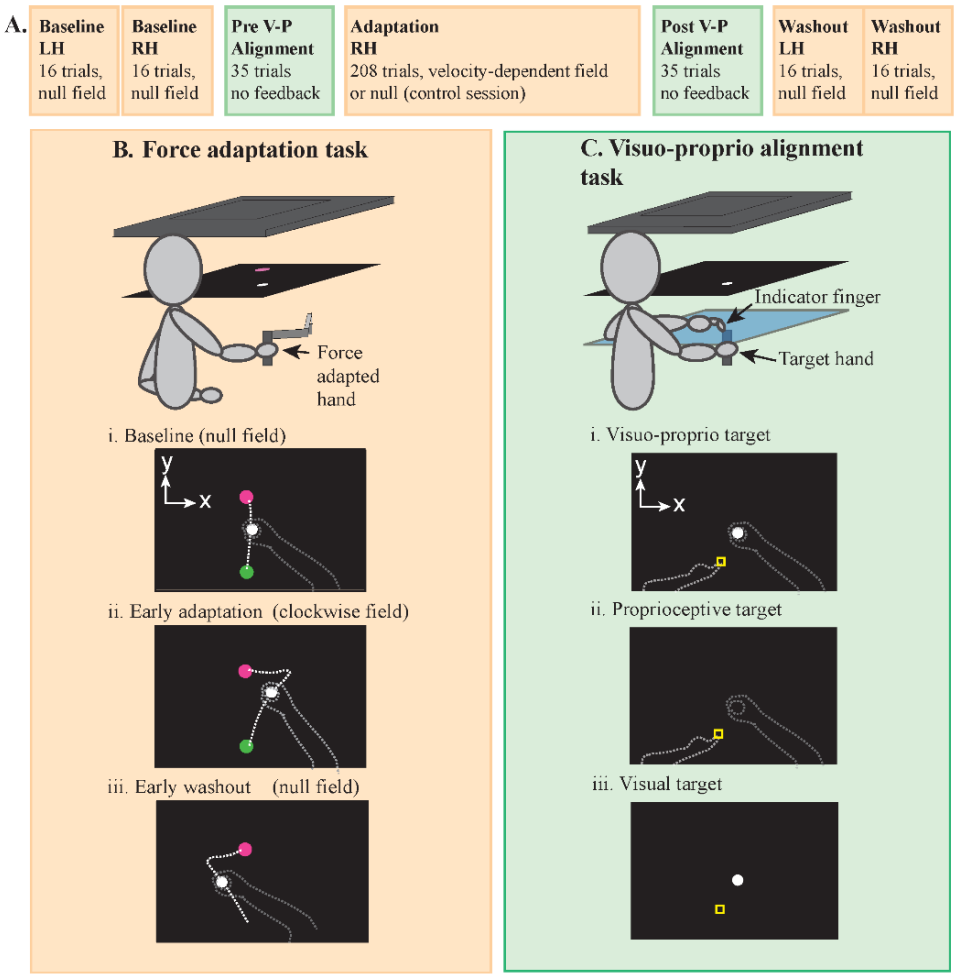

Figure 1. Experimental design. Subjects had no direct vision of either hand at any time. A) Single session protocol. Subjects completed five blocks of the reaching task (orange) and two blocks of the sensory alignment task (green) in each session. B) Force adaptation reaching task. Subjects were seated in front of a reflected rear projection apparatus. Subjects were instructed to make a series of straight ahead movements. A white circle was displayed over the center of the manipulandum handle throughout the task. The robotic manipulandum pushed subjects to the start position (green dot). A target then appeared 20 cm away from the start positon (pink dot). Subjects were instructed to reach to this target within 575-650 ms. Bi) Baseline reaches with each hand. Subjects had small perpendicular error during this block. Bii) During early adaptation, subjects had large initial errors that would become similar to baseline performance at the end of adaptation. Biii) During early washout subject experienced a negative after effect. C) Sensory alignment task. The left indicator hand remained above the touchscreen and below the mirror while the right target hand remained below the touchscreen. B) The three sensory target types. Ci) VP target. A white dot appeared above the robotic manipulandum, which was grasped by the right hand, and subjects were instructed to point with their left index finger to where the white dot was on top of the right hand. Cii) P target. Subjects pointed to their right hand with no visual information. Ciii) V target. Subjects pointed to a white dot with their right hand down in their lap. Yellow square varied in position and was the starting point for the indicator finger.

Reaching task design. Subjects grasped the manipulandum handle and made a series of straight-ahead movements to hit a visual target (Figure 1 B). A white circle was displayed over the center of the manipulandum handle throughout the task, but the mirror in which subjects viewed the task display was opaque such that subjects' hands were never visible (Figure 1 B). Subjects first completed a 16-trial baseline block with each hand (Figure 1 Bi). The adaptation block consisted of 208 trials with the right hand. During the adaptation block of the real force session only, subjects experienced a leftward or rightward velocity-dependent force field (Figure 1 Bii):

$$\begin{bmatrix} f_x \\ f_y \end{bmatrix} = D \begin{bmatrix} 0 & 18 \\ -18 & 0 \end{bmatrix} \begin{bmatrix} v_x \\ v_y \end{bmatrix} \quad (1)$$

where f_x and f_y are the commanded force to the manipulandum in the lateral (x) and sagittal (y) (Figure 1B) directions, v_x and v_y are hand velocities, and D is the force direction (1 for clockwise/rightward deflection, -1 for counter-clockwise/leftward deflection). Finally, subjects performed a 16-trial block with each hand in a null field to unlearn or washout the adaptation (Figure 1 Biii). Subjects were instructed that speed was very important for this task and were given feedback about movement speeds that were too fast, too slow, or within the desired timeframe of 575-650 ms.

Reaching task analysis. The maximum perpendicular deviation of the manipulandum from a straight-line path was computed for each trial of the reaching task. Adaptation magnitude and after-effect were calculated for each session. For both right and left hands, after-effect was calculated by subtracting the mean max perpendicular deviation from the first eight trials of the washout block from the mean of the last eight trials of baseline. Adaptation magnitude was

calculated for the right hand by subtracting the mean max perpendicular deviation of the first eight adaptation block trials from the last eight adaptation block trials.

Sensory alignment task design. Immediately before and after the force adaptation block, subjects performed a sensory estimation task to assess the spatial alignment of visual and proprioceptive estimates of their right hand position (Figure 1C). Subjects used their left (indicator) finger to point to a series of three target types on a touchscreen: a visuo-proprioceptive target (white circle displayed directly above their right hand, which grasped a replica BKIN manipulandum handle beneath the touchscreen glass) (Figure 1 Ci); proprioceptive-only target (right hand grasping the replica handle, with no white circle) (Figure 1 Cii); and a visual-only target (white circle alone) (Figure 1 Ciii). Subjects were given no feedback about performance during this task and had no vision of either hand. To adequately familiarize subjects with this task, they did a 40 trial practice block before their first session. Before and after the force adaptation block, subjects completed 15 visual-only (V), 15 proprioceptive-only (P), and 5 visuo-proprioceptive (VP) trials, in pseudorandom order. Subjects were instructed to take their time and be as accurate as possible.

Sensory alignment task analysis. Visual and proprioceptive realignment were calculated by subtracting the mean proprioceptive or visual endpoint of the pre-adaptation sensory alignment trials from the post-adaptation trials.

$$\Delta Px = Px_{post} - Px_{pre} \quad (2)$$

$$\Delta Vx = Vx_{post} - Vx_{pre} \quad (3)$$

ΔPx is proprioceptive realignment in the x-dimension while Px_{post} and Px_{pre} represent the mean proprioceptive x-dimension endpoint before and after force field learning. ΔVx is visual

realignment while Vx_{post} and Vx_{pre} represent the mean visual endpoint before and after force field learning. As has been done previously, we focused on the lateral dimension (x-dimension), as it was in this dimension that subjects experienced the force perturbation while reaching straight ahead.

We also computed an estimate of subjects' weighting of vision vs. proprioception (Wv) when both modalities were available, on VP targets. This method takes advantage of subjects' natural spatial biases that differ when pointing to visual compared to proprioceptive targets (Figure 2). Wv was calculated using the formula:

$$Wv = \frac{(y_P - y_{VP})}{[(y_V - y_{VP}) + (y_P - y_{VP})]} \quad (4)$$

where $(y_p - y_{vp})$ is the 2D distance between the mean P and VP endpoints and $(y_v - y_{vp})$ is the 2D distance between the mean V and VP endpoints (Figure 2) (Block & Bastian, 2010, 2011). If Wv equals one, this means a subject is relying fully on vision. If Wv equals zero, they are relying fully on proprioception. Wv equals 0.5 means a subject is relying equally on vison and proprioception. An increase in Wv after adaptation suggests an increased reliance on vision, whereas a negative ΔWv suggests an increased reliance on proprioception.

A mixed model repeated measures ANOVA was performed on each of ΔPx, ΔVx, and ΔWv, with session (real vs. null) as a within-subjects factor and group or force direction (leftward vs. rightward) as a between-subjects factor. Previous studies have found that proprioception shifted in the direction opposite the force field (e.g., leftward after adapting to a rightward field), so we expected a significant session*force direction interaction for ΔPx if our paradigm reproduced this result. A session*force direction interaction for ΔVx would suggest that visual estimates experience realignment in the same way that proprioceptive estimates do.

We would not predict ΔWv to be related to force direction, but we did expect an increase in Wv in response to any force field, which is a somatosensory perturbation. This would be indicated by a significant main effect of session for ΔWv. To illustrate the three outcome variables, real session was compared to the null session (e.g., $\Delta Px_{real} - \Delta Px_{null}$).

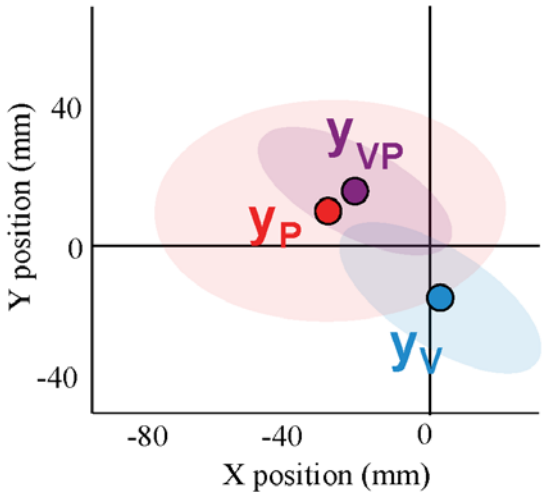

Figure 2. An example subject's pointing data on the visuo-proprioceptive alignment task. With the target always at the origin, different perceptual biases are seen depending on whether the target is perceived visually (blue), proprioceptively (red), or both (purple). This allows us to assess the subjects reliance on vision vs. proprioception (Wv). Filled circles are mean endpoint position of the indicator finger. Shaded regions represent 95% confidence ellipses.

Results

Reaching task. Subjects adapted to the rightward or leftward force perturbation in the real session (Figure 3). During baseline, both leftward and rightward groups had small perpendicular errors. When the force was introduced, the rightward group had large initial rightward errors while the leftward group had large initial leftward errors. At the end of the adaptation block, both groups had compensated for the perturbation. In the real force sessions, adaptation magnitude was 15.9 ± 5.06 mm (mean ± SE) for the rightward force group and 18.0 ± 3.7 mm (mean ± SE) for the leftward force group. During the washout block with the right hand there was some evidence of a negative after effect in the real force session. This was 0.13 ± 1.7 mm (mean ± SE) for the rightward group and 4.6 ± 10.4 mm (mean ± SE) for the leftward group.

Sensory alignment task. On the sensory alignment task, most subjects exhibited a leftward shift in Px and Vx following a rightward force field and a rightward shift in Px and Vx following a leftward force field, compared to the null session (Figure 4). At the group level, proprioceptive (Figure 5) and visual (Figure 6) estimates of right hand position realigned in the opposite direction of the force field, compared to the null session. The leftward force-field group experienced a 4.4 ± 2.6 mm proprioceptive shift to the right and a 3.4 ± 1.8 mm visual shift to the right. The rightward group experienced a 2.1 ± 2.4 mm proprioceptive shift to the left and a 2.3 ± 1.9 mm visual shift to the left relative to the null session. There was a significant session*force direction interaction in ΔVx ($F(1,34) = 4.9$, $p = 0.033$). There was no significant main effect of session ($F(1,34) = 0.19$, $p = 0.67$) or force direction ($F(1,34) = 1.5$, $p = 0.23$) on ΔVx. Effect size partial $\eta^2 = 0.13$ for ΔVx. In ΔPx, there was a trend in main effect of force direction ($F(1,34) = 3.0$, $p = 0.090$) and session*force direction interaction ($F(1,34) = 3.3$ p =

0.077). There was no main effect of session ($F(1,34) = 0.42$, $p = 0.52$) on ΔPx. Effect size partial $\eta^2 = 0.089$ for ΔPx.

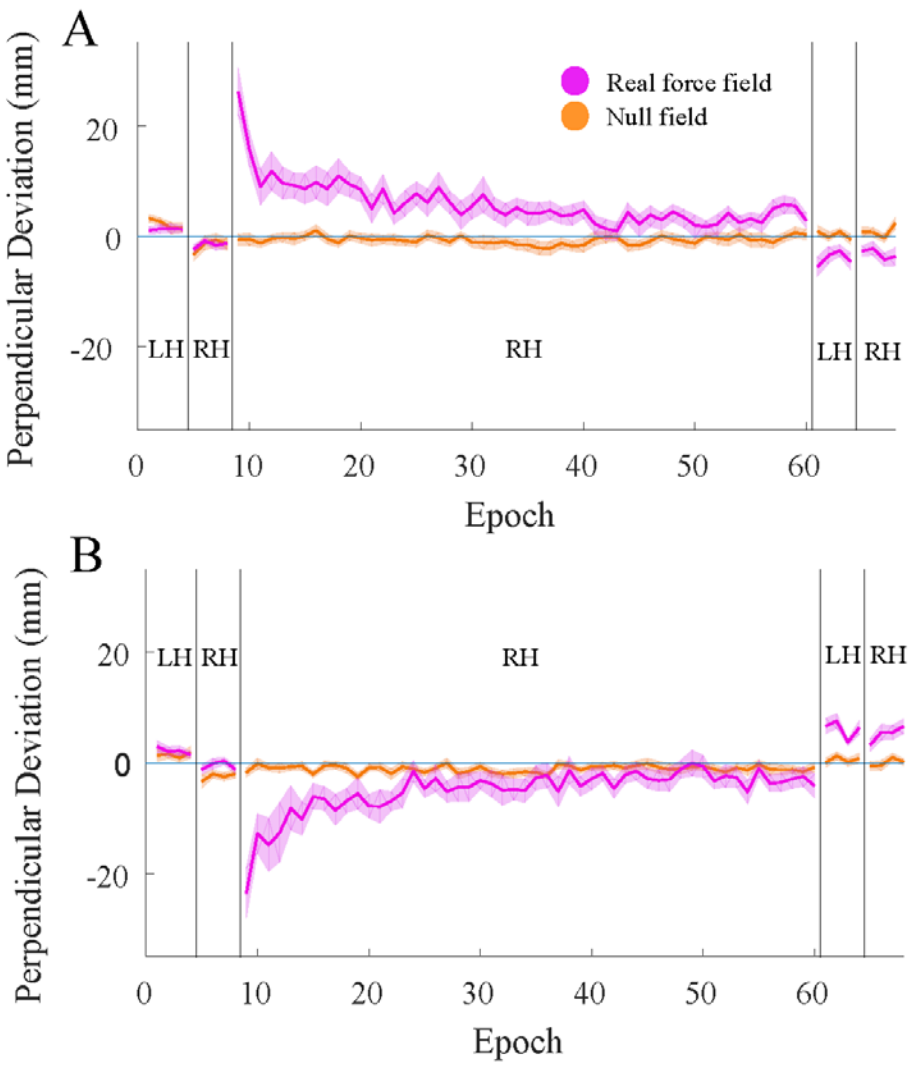

Figure 3. Force field adaptation curves, mean ± standard error. Perpendicular deviation during the force adaptation task averaged in epochs of four trials. The x-axis for both figures represents an epoch of four trials. The y-axis is the averaged perpendicular deviation across those four trials. Positive values indicate perpendicular deviation to the right and negative values indicate perpendicular deviation to the left. A) Rightward force field group. During baseline, both left and right hands experienced very small perpendicular deviation. During the adaptation block of the real force session (pink), the rightward group had large initial rightward perpendicular deviation that became similar to baseline performance toward the end of the adaptation block. In the washout blocks, there is some indication of a negative aftereffect for both hands. During the null session (orange), perpendicular errors were small throughout. B) Leftward force field. During baseline, both left and right hands experienced very small perpendicular deviation. During the adaptation block, there were large initial leftward perpendicular deviations that became similar to baseline performance toward the end of the force field block. In the washout blocks, there is some indication of a negative aftereffect for both hands. During the null session (orange), perpendicular errors were small throughout.

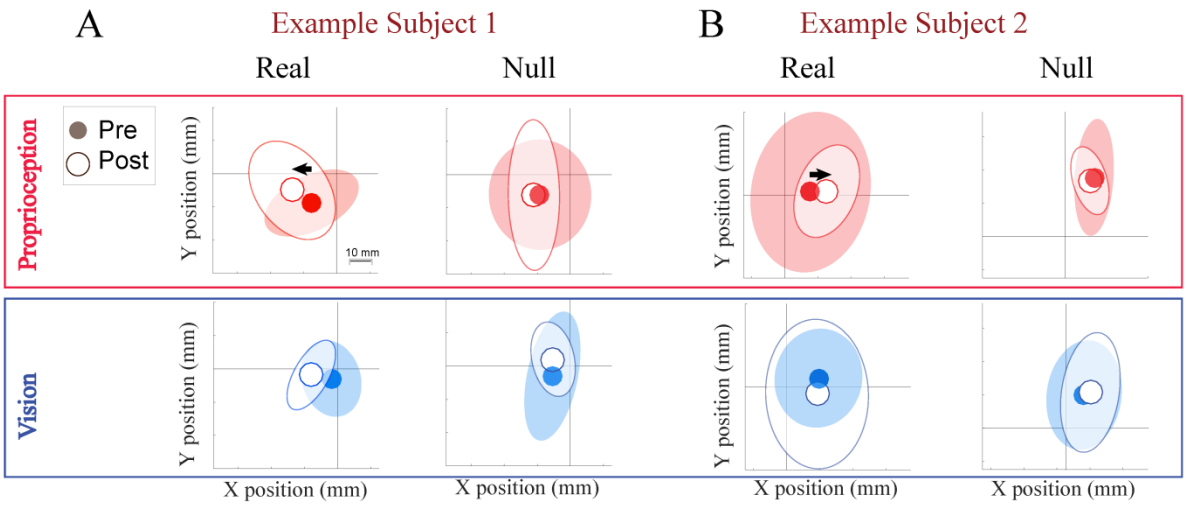

Figure 4. Example subjects on the sensory alignment task. The top row represents proprioceptive alignment and the bottom row represents visual alignment. The origin is the location of the target. The colored circle represents their mean proprioceptive or visual estimate with 95% confidence ellipse pre-adaptation block. The white circle represents mean estimates post-adaptation block. A) Rightward force field. Following a rightward force field, this subject's Px and Vx shifted leftward (opposite direction of the force). There was no change in Px or Vx following a null field. B) Leftward force field. There was a rightward shift in proprioception following force field learning. However, there was no apparent change in Vx.

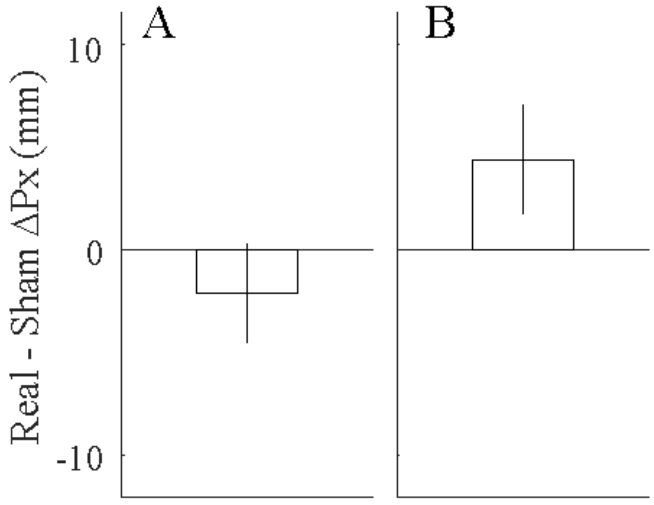

Figure 5. Proprioceptive realignment for rightward (A) and leftward (B) force fields. Mean ± standard error. The y-axis represents proprioceptive realignment in the real relative to the null session. Negative values indicate leftward proprioceptive realignment and positive values indicate rightward proprioceptive realignment. Relative to the null session, subjects experiencing a rightward force field had a leftward shift in proprioception. Subjects experiencing a leftward force field had a rightward shift.

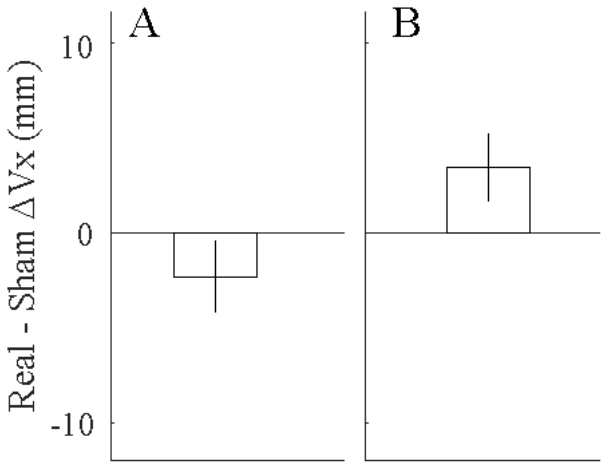

Figure 6. Visual realignment for rightward (A) and leftward (B) force fields. Mean ± standard error. The y-axis represents visual realignment in the real relative to the null session. Negative values indicate leftward visual realignment and positive values indicate rightward visual realignment. Relative to the null session, subjects experiencing a rightward force field had a leftward realignment in vision. Subjects experiencing a leftward force field had a rightward realignment.

Changes in weight of vision from pre- to post-adaptation were not consistent across groups. The leftward group experienced a 0.10 +- 0.067 increase in Wv and the rightward group experienced a 0.031 ± 0.067 increase in Wv (Figure 7). There was no main effect of session on ΔWv ($F(1,34) = 2.0$, $p = 0.17$). There was no main effect of force direction ($F(1,34) = 0.47$, $p = 0.50$) or session*force direction interaction ($F(1,34) = 0.59$, $df = 1$, $p = 0.45$). Effect size partial $\eta^2 = 0.017$ for ΔWv.

On the reaching task, negative aftereffect in the left hand was computed because the left hand indicates the position of the targets (P, V, and VP) during the sensory alignment task. Because the left hand was never exposed to the force perturbation, the presence of left hand negative aftereffect suggests the presence of intermanual transfer of motor learning from the right to the left hand, meaning that the left hand may not be a reliable indicator of sensory perception about the right hand. To explore the extent to which left hand transfer may have influenced the ΔPx we measured, we computed correlations between left hand aftereffect magnitude and ΔPx in each session. There was no significant transfer to the left hand during any of the sessions.

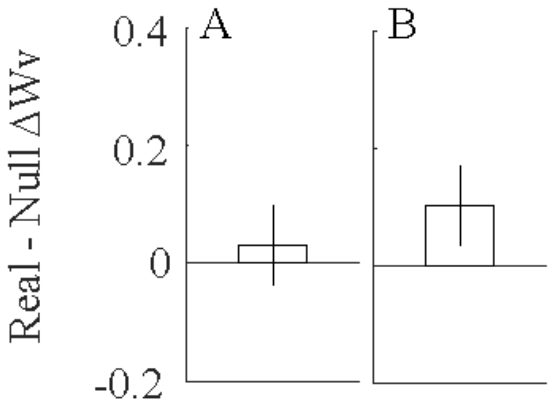

Figure 7. Change in weight of vision versus proprioception (Wv) for rightward (A) and leftward (B) force fields. Mean ± standard error. The y-axis represents ΔWv in the real relative to the null session. Negative values indicate a reduction in Wv (relying more on proprioception) while positive values represent an increase in Wv (relying more on vision). Relative to the null session, in the real session both groups experienced an increase in Wv on average.

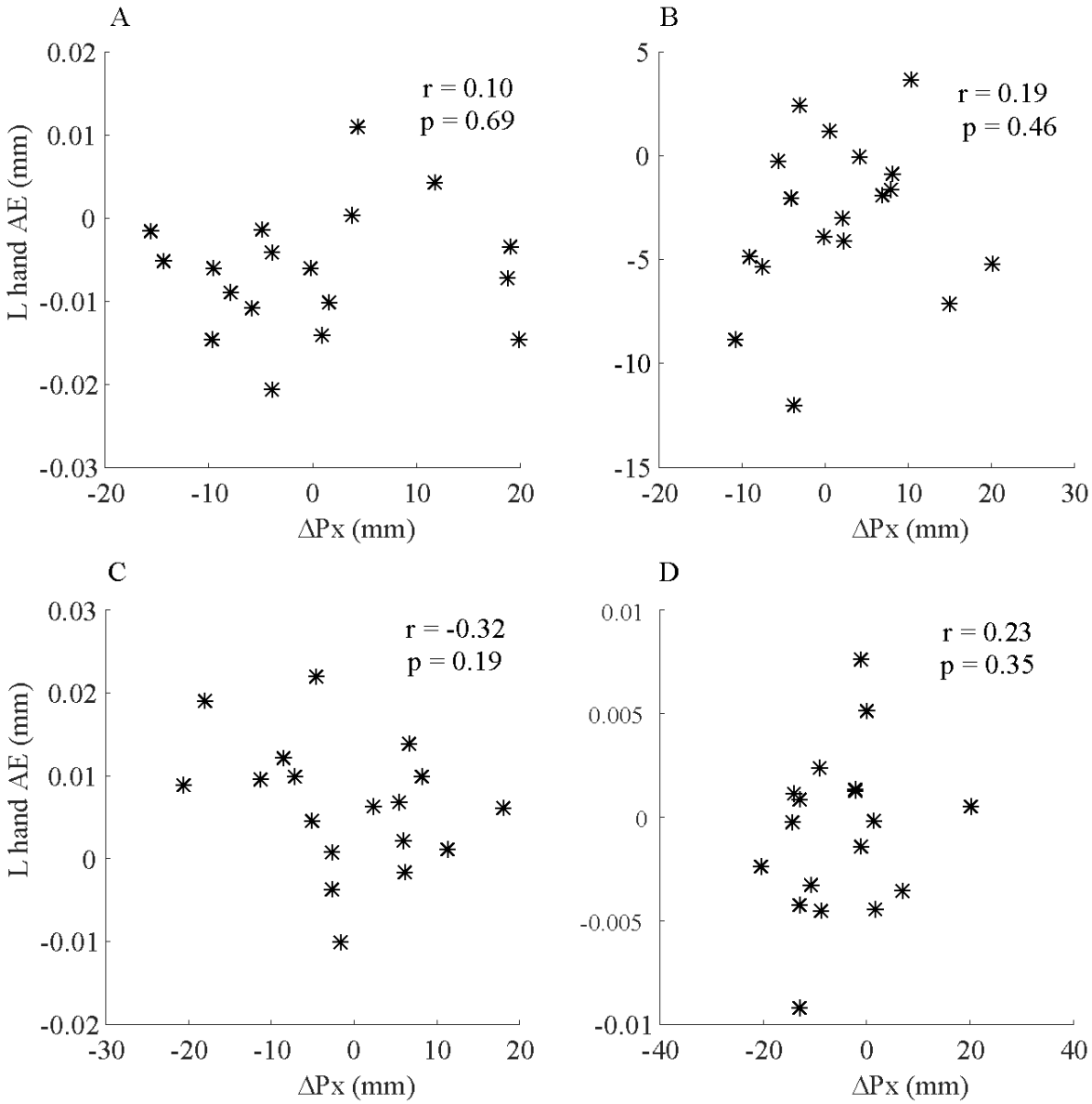

Figure 8. Left hand after effect (AE) versus ΔPx for all session types. For all panels, ΔPx is on the x-axis and represents proprioceptive realignment (post – pre) during a single session. The y-axis is the left hand after effect. A) Real session for the rightward force group. B) Null session for the rightward force group. C) Real session for the leftward force group. D) Null session for the leftward force group.

Discussion

In this experiment, we examined the multisensory effects of motor learning. Vision and proprioception realigned in the opposite direction of the force with a magnitude similar to that observed with proprioception in the literature (Ostry et al., 2010). However, the current version of our paradigm had greater between-subject variance compared to the study by Ostry et al., 2010.

Motor learning may alter sensory systems. Perceptual changes have been suggested in human (Ostry et al., 2010) and animal studies (Xerri, Merzenich, Jenkins, & Santucci, 1999) following motor learning. Xerri et al., 1999, trained monkeys to pick up food pellets. As the monkeys learned to effectively pick up the pellets, they began using much smaller regions of their fingers to pick up the pellets. The corresponding representations in S1 grew about two times larger than the same S1 fingertip regions for the contralateral hand, suggesting an effect of motor learning on the somatosensory system (Xerri et al., 1999). Ostry et al., 2010 instructed subjects to make straight-ahead reaches with and without a sensorimotor perturbation. Before and after force field learning, they found subjects' perceptual boundary shifted about 2mm in the opposite direction of the force they adapted to, suggesting that force field learning may alter proprioception (Ostry et al., 2010). These perceptual changes may be due to changes in somatosensory cortex (S1), primary motor cortex (M1), or both (Ostry et al., 2010). Our finding of a 2-4mm shift in proprioceptive estimates in the opposite direction of the force field was not statistically significant, but this trend is consistent with Ostry et al. (2010). Our finding of a shift in visual estimates with the same magnitude and direction suggests that force field learning has multisensory effects, with proprioceptive realignment matched by visual realignment.

We predicted that subjects would rely more on vision following force field learning. There is ample evidence suggesting subjects increase reliance on the less variable modality following a perturbation. Mahboobin, Loughlin, Redfern, & Sparto, 2005; Patel, Gomez, Lush, & Fransson, 2009 suggested increased reliance on vision when proprioception is impaired. Perturbing the somatosensory system makes it less reliable which increases reliance on the visual and vestibular systems (Mahboobin et al., 2005). The somatosensory perturbation in this study may have made proprioception less reliable. Although we did not find a significant increase in Wv during the real force field session, one possible explanation is multisensory reweighting deficit (Jeka et al., 2006). In the present study, multisensory reweighting deficit could have made subjects unable to switch from imprecise proprioceptive information to more precise visual information following force field adaptation. However, multisensory reweighting deficit is typically seen in elderly subjects who do not up-weight proprioceptive information in the presence of inaccurate visual information (Jeka et al., 2006). A more likely possibility is that the force field perturbation in the present study was not a strong enough somatosensory perturbation to elicit significant up-weighting of vision. A study using a stronger force field might find greater up-weighting of vision.

I piloted nine versions of this task, as the first eight versions were unable to reproduce the proprioceptive changes reported in the literature. Each subsequent version was modified to reduce noise or to make our sensory and motor tasks more compatible (Ostry, Darainy, Mattar, Wong, & Gribble, 2010). Noise in an adaptation paradigm can come from both motor and sensory sources (Harris & Wolpert, 1998; van der Kooij & Peterka, 2011). In adaptation paradigms involving a somatosensory perturbation, the noise of sensory systems is due to inherent noise in each sensory modality as well as variability from the stimulus evoked

perturbation (van der Kooij & Peterka, 2011). Motor noise and the application of a continuous perturbation may significantly increase the noise (van der Kooij & Peterka, 2011). One way to account for this increased variability is to down-weight the perturbed sensory system (van der Kooij & Peterka, 2011). We made several changes to our paradigm to reduce noise in the motor task in an attempt to get clearer sensory effects. In the reaching task, we originally had four start and target positions to discourage subjects from memorizing a particular reach direction. However, each reach on the robot during adaptation did not result in the same perturbation in the X-dimension with this setup. We therefore changed to one start and one target position, deciding it was more important to have a consistent perturbation. The number of adaptation trials was also increased to ensure subjects were fully adapted before performing the post sensory task. To be more like Ostry et al., 2010, the force perturbation was made into a velocity dependent curl field with rightward being clockwise and leftward being counterclockwise. Previous versions used a velocity dependent force, but the perturbation was right or left instead of clockwise or counterclockwise. In the sensory task, a potential source of variability was the fixation cross. The fixation cross did influence some subjects' pointing during the sensory task. We removed the fixation cross for version four, but we realized we then could not control where subjects looked, and eye position is a possible confound when visually estimating hand position. In version five, we therefore replaced the fixation cross with the word "EYES" to remind subjects this is where their eyes go, not their reaching hand.

Many of the task modifications were aimed at making the sensory and motor task contexts more similar. Context is the set of situational elements in which motor learning takes place (Mitchell, Macrae, & Banaji, 2004). Changes in context can occur in the sensory environment, type of movement or body posture or position, and other factors. When we interact

with objects, the context of our movements may change in subtle ways (Wolpert & Ghahramani, 2000). In some situations it is crucial to generalize a skill learned in a specific context to other contexts (Schmidt & Bjork, 1992). This is especially important in physical therapy where patients need to be able to transfer learning from a robot or other therapeutic instrument to daily living (Torres-Oviedo & Bastian, 2012).

Motor learning is known to be context-specific, and there is evidence that the proprioceptive changes observed after motor learning may also be context-specific (Vahdat, Darainy, & Ostry, 2014). Prior learning may affect motor learning generalization. In a visuomotor rotation task, subjects were asked to control a cursor by making reaching movements with the shoulder and elbow or the wrist (Krakauer, Mazzoni, Ghazizadeh, Ravindran, & Shadmehr, 2006). The order of training affected learning in different contexts. Subjects training shoulder and elbow movements on day one were able to transfer this learning to the wrist on day two (Krakauer et al., 2006). Subjects training wrist movements first experienced no significant transfer to the shoulder or elbow on day two (Krakauer et al., 2006). Subjects with a history of repetitive wrist movement, such as tennis players, were unsuccessful in generalizing learning to the arm (Krakauer et al., 2006).

Sources of error or variability may affect generalization of learning to new or different contexts. Torres-Oviedo & Bastian, 2012 investigated how manipulating error size and variability while adapting on a split belt treadmill may transfer to over-ground walking. Subjects whose errors were within their normal limits were able to successfully transfer the adapted walking pattern over ground (Torres-Oviedo & Bastian, 2012). Subjects who adapted to larger than normal errors on the treadmill were not successful in transferring the learned pattern to over ground (Torres-Oviedo & Bastian, 2012).

Learned reaching movements can generalize to greater distances or shorter durations (Goodbody & Wolpert, 1998) in the trained workspace (Gandolfo, Mussa-Ivaldi, & Bizzi, 1996). Subjects completed a point-to-point reaching force field adaptation task (Goodbody & Wolpert, 1998) or a center-out reaching task (Gandolfo et al., 1996). Making a faster reach produced an aftereffect suggesting the learned movement generalized to faster reaches with no perturbation (Goodbody & Wolpert, 1998). However, adaptation deteriorated as the distance from the learned workspace increases (Gandolfo et al., 1996).

We made many modifications to the experimental paradigm for the purpose of making the sensory and motor task contexts more similar. In version one, subjects used their right index finger as the target on the sensory task. During the robot task, subjects grasped the robotic manipulandum with the whole hand. By having subjects make a fist and use their right thumb as the target in version two, this made the robot and sensory tasks more analogous in terms of arm posture. Single unit recordings from S1 have suggested cells are tuned for specific movement directions that change excitability as arm posture changes (Prud'homme & Kalaska, 1994), which may affect learned changes. Subjects grasped a replica robotic manipulandum handle during the sensory task in version seven. Using a handle in the sensory task like the one on the robot provided tactile feedback similar to the robotic manipulandum and kept the hand and arm in a posture more like that in the reaching task. Keeping the hand and arm in the same position, as well as providing similar tactile feedback in both tasks, may improve subject's ability to detect their target hand (Wolpert, Doya, & Kawato, 2003).

In versions 1-5, subjects did the sensory task on a touchscreen apparatus that was a short walk from the robotic apparatus where they did the reaching task. This allowed subjects to see their hands which may have reduced any sensory changes caused by the force adaptation task. In

version six, subjects were blindfolded as they walked from the touchscreen apparatus to the robot. This was done to keep subjects from seeing their hands: Providing subjects with visual feedback of their actual hand position following force field adaptation could update the internal representation of their hand (Ghez, Gordon, & Felice Ghilardi, 1995), affecting subjects' perceived hand position during the sensory estimation task. In version nine, subjects completed all trials on the sensory task and robot task in the same position. To keep the context similar between both tasks, a smaller touchscreen for the sensory task was placed at the same level as the robot manipulandum on the robot. After getting more information from Dr. David Ostry (Ostry et al., 2010) about their protocol, we decided to restrain subjects at the waist, shoulder, and head when completing the sensory and robot tasks in version nine. This was done to ensure that subjects only moved their arms and to reduce any noise trunk movements might introduce. Having subjects complete both the sensory and motor tasks with the same arm posture and restraint was done to ensure contextual similarity between the sensory and motor tasks. This means the motor memory encoded during the motor adaption task should be available during the sensory task due to the encoding specific principle (Mitchell et al., 2004). This principle states that information that is encoded will be available when retrieved (Mitchell et al., 2004). Performing both tasks in the same context where information was encoded should promote similar retrieval during either task (Mitchell et al., 2004).

Even with all these task modifications aimed at reducing noise and making the contexts of the motor and sensory tasks more similar, the observed changes in proprioceptive estimates did not rise to the level of significance. This may be due to noise in the sensory task that was not present in the Ostry et al. study (2010). Ostry et al., 2010 obtained sensory estimates by having the limb that underwent force field adaptation perform a proprioceptive psychometric function

task. The major source of noise would be sensory information from the dominant limb, which was passively moved by the robot. In the present sensory task with the left finger used to indicate perception of the right hand (version 9), we have sensory noise from both hands, as well as motor noise from the indicator hand, which may explain the high variability in proprioceptive realignment among subjects.

An additional potential problem with the current sensory task is that any intermanual transfer to the left hand would bias the sensory estimates. This is unlikely to occur because proprioceptive realignment (Henriques & Cressman, 2012) and motor adaptation do not transfer well to movements with different kinematics or contexts (Martin, Keating, Goodkin, Bastian, & Thach, 1996), and the movements of the left hand in the sensory task differ in posture, orientation, and movement path from the robot task. If any transfer were to occur, it should be very small. In the present study, all sessions showed no significant correlation between proprioceptive realignment and left hand transfer. While there were not any significant correlations, this is still a potential issue in the current paradigm.

To eliminate the noise and potential for intermanual transfer associated with the left hand, future versions of this experiment will be conducted utilizing psychometric tasks to obtain sensory estimates. I have programmed three different protocols on the robot to obtain proprioceptive (P), visual (V), and visuoproprioceptive (VP) estimates. P estimates will be obtained by the subject holding on to the robotic manipulandum with their right hand before and after force adaptation. The robot will move the subject's hand to a sequence of test positions and, each time, we will ask the subject if that position is left or right of their body midline. VP estimates will be obtained just as the proprioceptive estimates, but a white circle will be on top of the manipulandum. To obtain V estimates, subjects will not hold on to the robotic

manipulandum. A white circle will appear on the monitor and subjects will say if the white circle is left or right of their body midline. All movements of the sensory targets will only occur in the X-dimension.

Conclusion

We asked whether force field adaptation affects multisensory perception. Given that multisensory integration plays a key role in movement planning, one possibility is that force field adaptation affects all relevant sensory modalities similarly. Alternatively, the sensory effects of force adaptation may be specific to proprioception. Group results suggest that both visual and proprioceptive estimates of right hand position tended to be systematically realigned after force field learning, supporting the first hypothesis. Realignment was in the opposite direction of the force field, consistent with previous literature. This study supports the idea that motor learning has multisensory effects.

References

Block, H. J., & Bastian, A. J. (2010). Sensory reweighting in targeted reaching: effects of conscious effort, error history, and target salience. *J.Neurophysiol.*, *103*(1), 206–217.

Block, H. J., & Bastian, A. J. (2011). Sensory weighting and realignment: independent compensatory processes. *J.Neurophysiol.*, *106*(1), 59–70.

Brown, L. E., Wilson, E. T., Goodale, M. A., & Gribble, P. L. (2007). Motor force field learning influences visual processing of target motion. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *27*(37), 9975–9983. https://doi.org/10.1523/JNEUROSCI.1245-07.2007

Carey, L. M., & Matyas, T. A. (2011). Frequency of discriminative sensory loss in the hand after stroke in a rehabilitation setting. *Journal of Rehabilitation Medicine*, *43*(3), 257–263. https://doi.org/10.2340/16501977-0662

Gandolfo, F., Mussa-Ivaldi, F. A., & Bizzi, E. (1996). Motor learning by field approximation. *Proceedings of the National Academy of Sciences of the United States of America*, *93*(9), 3843–3846.

Ghahramani, Z., Wolpert, D. M., & Jordan, M. I. (1997). Computational models for sensorimotor integration. In P. G. Morasso & V. Sanguineti (Eds.), *Self-Organization, Computational Maps and Motor Control* (pp. 117–147). Amsterdam: North-Holland.

Ghez, C., Gordon, J., & Felice Ghilardi, M. (1995). Impairments of reaching movements in patients without proprioception. II. Effects of visual information on accuracy. - PubMed - NCBI. Retrieved June 22, 2017, from https://www.ncbi.nlm.nih.gov/pubmed/7714578

Goodbody, S. J., & Wolpert, D. M. (1998). Temporal and Amplitude Generalization in Motor Learning. *Journal of Neurophysiology*, *79*(4), 1825–1838.

Harris, C. M., & Wolpert, D. M. (1998). Signal-dependent noise determines motor planning. *Nature*, *394*(6695), 780–784. https://doi.org/10.1038/29528

Henriques, D. Y. P., & Cressman, E. K. (2012). Visuomotor adaptation and proprioceptive recalibration. *Journal of Motor Behavior*, *44*(6), 435–444. https://doi.org/10.1080/00222895.2012.659232

Jeka, J., Allison, L., Saffer, M., Zhang, Y., Carver, S., & Kiemel, T. (2006). Sensory reweighting with translational visual stimuli in young and elderly adults: the role of state-dependent noise. *Experimental Brain Research*, *174*(3), 517–527. https://doi.org/10.1007/s00221-006-0502-y

Krakauer, J. W., Mazzoni, P., Ghazizadeh, A., Ravindran, R., & Shadmehr, R. (2006). Generalization of Motor Learning Depends on the History of Prior Action. *PLOS Biology*, *4*(10), e316. https://doi.org/10.1371/journal.pbio.0040316

Leichnetz, G. R. (2001). Connections of the medial posterior parietal cortex (area 7m) in the monkey. *The Anatomical Record*, *263*(2), 215–236. https://doi.org/10.1002/ar.1082

Mahboobin, A., Loughlin, P. J., Redfern, M. S., & Sparto, P. J. (2005). Sensory re-weighting in human postural control during moving-scene perturbations. *Experimental Brain Research*, *167*(2), 260–267. https://doi.org/10.1007/s00221-005-0053-7

Martin, T. A., Keating, J. G., Goodkin, H. P., Bastian, A. J., & Thach, W. T. (1996). Throwing while looking through prisms. II. Specificity and storage of multiple gaze-throw calibrations. *Brain: A Journal of Neurology*, *119 (Pt 4)*, 1199–1211.

Mattar, A. A. G., Darainy, M., & Ostry, D. J. (2013). Motor learning and its sensory effects: time course of perceptual change and its presence with gradual introduction of load. *Journal of Neurophysiology*, *109*(3), 782–791. https://doi.org/10.1152/jn.00734.2011

Miller, M. W., & Vogt, B. A. (1984). Direct connections of rat visual cortex with sensory, motor, and association cortices. *The Journal of Comparative Neurology*, *226*(2), 184–202. https://doi.org/10.1002/cne.902260204

Mitchell, J., Macrae, N., & Banaji, M. (2004). Encoding-specific effects of social cognition on the neural correlates of subsequent memory. Retrieved June 22, 2017, from http://cat.inist.fr/?aModele=afficheN&cpsidt=15799274

Nasir, S. M., & Ostry, D. J. (2009). Auditory plasticity and speech motor learning. *Proceedings of the National Academy of Sciences*, *106*(48), 20470–20475. https://doi.org/10.1073/pnas.0907032106

Ostry, D. J., Darainy, M., Mattar, A. A. G., Wong, J., & Gribble, P. L. (2010). Somatosensory plasticity and motor learning. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*, *30*(15), 5384–5393. https://doi.org/10.1523/JNEUROSCI.4571-09.2010

Ostry, D. J., & Gribble, P. L. (2016). Sensory Plasticity in Human Motor Learning. *Trends in Neurosciences*, *39*(2), 114–123. https://doi.org/10.1016/j.tins.2015.12.006

Patel, M., Gomez, S., Lush, D., & Fransson, P. A. (2009). Adaptation and vision change the relationship between muscle activity of the lower limbs and body movement during human balance perturbations. *Clinical Neurophysiology: Official Journal of the International Federation of Clinical Neurophysiology*, *120*(3), 601–609. https://doi.org/10.1016/j.clinph.2008.11.026

Prud'homme, M. J., & Kalaska, J. F. (1994). Proprioceptive activity in primate primary somatosensory cortex during active arm reaching movements. *Journal of Neurophysiology*, *72*(5), 2280–2301.

Schmidt, R. A., & Bjork, R. A. (1992). New Conceptualizations of Practice: Common Principles in Three Paradigms Suggest New Concepts for Training. *Psychological Science*, *3*(4), 207–218. https://doi.org/10.1111/j.1467-9280.1992.tb00029.x

Torres-Oviedo, G., & Bastian, A. J. (2012). Natural error patterns enable transfer of motor learning to novel contexts. *Journal of Neurophysiology*, *107*(1), 346–356. https://doi.org/10.1152/jn.00570.2011

Vahdat, S., Darainy, M., & Ostry, D. J. (2014). Structure of Plasticity in Human Sensory and Motor Networks Due to Perceptual Learning. *The Journal of Neuroscience*, *34*(7), 2451–2463. https://doi.org/10.1523/JNEUROSCI.4291-13.2014

van der Kooij, H., & Peterka, R. J. (2011). Non-linear stimulus-response behavior of the human stance control system is predicted by optimization of a system with sensory and motor noise. *Journal of Computational Neuroscience*, *30*(3), 759–778. https://doi.org/10.1007/s10827-010-0291-y

Wolpert, D. M., Doya, K., & Kawato, M. (2003). A unifying computational framework for motor control and social interaction. *Philosophical Transactions of the Royal Society B: Biological Sciences*, *358*(1431), 593–602. https://doi.org/10.1098/rstb.2002.1238

Wolpert, D. M., & Ghahramani, Z. (2000). Computational principles of movement neuroscience. *Nature Neuroscience*, *3*, 1212–1217. https://doi.org/10.1038/81497

Xerri, C., Merzenich, M. M., Jenkins, W., & Santucci, S. (1999). Representational Plasticity in Cortical Area 3b Paralleling Tactual-motor Skill Acquisition in Adult Monkeys. *Cerebral Cortex*, *9*(3), 264–276. https://doi.org/10.1093/cercor/9.3.264